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Flight Technology Improvement

Proceedings of a workshop
held at College Park, Maryland
July 31-August 2, 1979

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Flight Technology Improvement

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and the Office of Space and Terrestrial
Applications of NASA Headquarters and
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and held at College Park, Maryland,
July 31-August 2, 1979

National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1979

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PREFACE

The National Aeronautics and Space Administration sponsored a Flight Technology Improvement Workshop at the University of Maryland from July 31 to August 2, 1979. The purpose of the workshop was to bring together a group of space instrumentation experts from government and non-government agencies to discuss past spaceborne instrumentation technology deficiencies and current technology developments and to identify areas for potential improvement for future flight missions.

Approximately 80 individuals participated in four panels covering the technology areas of: Optical Radiometric Instrumentation and Calibration, Electromechanical Subsystems, Attitude Control and Determination, and Power Subsystems. The organization of the workshop and the participants are shown on the next page.

The members of the workshop panels made a large number of recommendations. Some of the significant requests were:

1) That current NASA policy regarding the use of only "space-proven" hardware in flight missions should be changed so that new technology developments can be used in space.

2) That radiometrics accuracy of instruments for upcoming flight programs should be improved and that calibration standards in conjunction with the National Bureau of Standards should be developed.

3) That contamination potential for radiometric instruments on the space Shuttle should be reduced so that cryogenically cooled remote sensors can operate effectively.

4) That high voltage power systems should be developed to obtain a higher kilowatt capability needed in future spacecraft systems.

The overall recommendations and conclusions of this workshop are presented in a summary which is placed at the beginning of this document. Detailed information regarding the discussions of each of the panels and the recommendations are contained in the main body of the report.

Warren A. Hovis, Jr.
General Chairman

Jules Lehmann
Charles E. Pontius
Leonard P. Kopia
Co-coordinators

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CHAPTER 1
SUMMARY OF THE FLIGHT TECHNOLOGY IMPROVEMENT WORKSHOP

INTRODUCTION

The Flight Technology Improvement Workshop, sponsored jointly by the Office of Aeronautics and Space Technology and the Office of Space and Terrestrial Applications of NASA Headquarters and the Langley Research Center, was held at the University of Maryland's Center of Adult Education in College Park, Maryland, July 31 to August 2, 1979.

The purpose of the workshop was to bring together space instrumentation technologists from government and industry in order to discuss past spaceborne instrument deficiencies and shortcomings and to recommend potential corrections and technology developments to offset the occurrence of such problems in the future. Approximately 80 individuals participated in the workshop - 27 from industry and the balance from the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the National Bureau of Standards, and the Department of Defense (Space and Missile System Organization and Naval Research Laboratory).

The workshop was organized into four panels covering specific problem areas: Optical Radiometric Instrumentation and Calibration, Electromechanical Subsystems, Attitude Control and Determination, and Power Subsystems. A series of technology recommendations for near-term consideration was developed by the panels and is contained in this document.

SUMMARY OF PANEL FINDINGS

This summary covers the highlights of the recommendations by the four panels of the Flight Technology Improvement Workshop. All of the recommendations fell into three general categories:

1) Policy changes needed to facilitate the use of improved or newly developed technology.
2) Development of new devices or techniques to meet new requirements.
3) Needed improvement or use of existing technology.

Reports of the individual panels, in considerably more detail, follow this summary. It should be recognized that each panel was asked at the beginning of the workshop to restrict their recommendations to only those items that they felt were of the most urgent nature to carry out the spacecraft programs being considered for the reasonably near future. Because of the request, it should be recognized that, even though recommendations are given in priority order, those at the bottom of the priority list are still important for successful completion of missions in the near future.

There were far more recommendations for technology improvements brought up by the members of the various Panels than could possibly be included in a report of this nature. The Panels themselves considered all of the recommendations, and selected only those they considered to be the most important to appear in the report. The practical limits of resources in manpower and funding were considered by all of the Panels in making the reports, and it is hoped that readers of this report will recognize that there are many other technical improvements that are, perhaps, needed or at least highly desirable, but that a shopping list of all technical improvements fitting those categories would be beyond the scope of the Panels' activities and would weaken the impact of this report by covering too many areas in too little detail.

Optical Radiometric Instruments and Calibration Panel Summary

The Optical Radiometric Instruments and Calibration Panel recognized that the present knowledge of in-orbit radiometric accuracy of sensors now in flight, or being prepared for flight, is poor, especially in view of requirements for monitoring of long-term changes in such areas as the measurement of the ozone concentration and in climate studies. In such areas, requirements for calibration and precision over long periods of time are found to exceed the state-of-the-art for radiometric components such as detectors, and for the calibration sources and transfer standards needed to calibrate new instruments.

In the area of improvement of existing technology, it was recognized that, although adequate standards exist at the National Bureau of Standards (NBS) for calibration of certain types of instruments, these standards are, in essence, point sources and are not appropriate for the calibration of the type of instruments planned now for the space program such as the ERBE instrument for the TIROS-N series, the Thematic Mapper for Landsat, the AVHRR (also for TIROS-N), and the SBUV that will fly on one of the NOAA satellites in the TIROS-N series. The Panel recommended that, in order to meet the requirements of long-term monitoring, new improved calibration standards are needed and the techniques for transferring the calibration to the spaceflight instruments will have to be developed. The NBS personnel participating on the Panel pointed out that the situation is particularly bad between .16 and 5 micrometers where reflectance of solar energy is the principal quantity measured. They also pointed out that it may be impossible to develop light sources themselves which are stable enough over that period of time necessary for the monitoring to be accomplished, but they felt that techniques such as reliance on very stable detectors, especially those of the silicon family, together with the improvement of sources, could provide the necessary radiometric accuracy over the periods of time needed. The NBS people felt that, with the proper support, they could serve as the keeper of the standards against which the radiometric measurements would be checked over the long period of time in order to determine if there were changes in such things as the ozone layer concentration and the albedo of the Earth.

The devices needed for calibration, both light sources and detectors, were felt to be principally improvements of existing technology. However, in the area of techniques, the Panel recognized that the NBS had little or no contact with the space program in developing mechanisms for transferring calibration from their sources which are essentially point sources to the instruments planned for flight in the space program. They propose that, as part of the Self-Study Manual on Radiometric Calibration that is prepared and distributed by the NBS, they, together with scientists from government installations, would devise standard techniques for transfer of calibration and publish these techniques as a part of the Self-Study Manual. These volumes of the Manual will then serve as a guide to assure that calibration is done in a uniform manner, regardless of what organization carries out the calibration.

It was recognized that development of long-term stable light sources for use as on-board calibration sources was an area where new technology should be developed, since all of the sources now in use are simply commercial light bulbs designed for some other purpose and adapted to the space program. The Panel also felt that emphasis should be placed on the development of optical components with long-term stability in the space environment but that some attempts to carry out such improvements had met with difficulty. In particular, a problem was noted with super-polished optics that had been developed to reduce scattering from the optical surfaces so as to minimize contamination of the signal by scattering. After development of the super-polished surfaces, it was found that a "blue haze" developed on them. The effect of and possible methods for prevention of the "blue haze" have not been determined, and study is needed in areas such as this where newly developed optical components present previously unnoticed problems.

The Panel identified two principal areas regarding policy change: First, the Panel felt that NASA should establish calibration facilities at those NASA centers that are required to carry out calibration of radiometric sensors, and that these calibration facilities should be standardized to the highest degree possible, both in equipment and techniques. In addition, it was felt that the NBS should serve as a consultant to advise on techniques and should also carry out checks of calibration sources at the various NASA centers. The Panel supported the concept of a highly stable instrument that would be developed by the NBS, and then carried to the various calibration laboratories at NASA centers to check calibration. The NBS personnel agreed that they would undertake such an activity if they were supported. In order to coordinate the requirements, for the establishment of facilities and the standardization of equipment and capabilities, the Panel identified the need for an Interagency/Intercenter Steering Group of NASA-NBS personnel covering the total range of measurement requirements.

The second area of policy change recommended was the establishment of a Solar Test Facility to be used by all NASA centers in light of the fact that it has been impossible to produce a source in the laboratory that simulates the Sun in intensity and spectral distribution. It was recommended that the existing NASA facility at Table Mountain in California be improved to include a tracker-mounted vacuum system so that instruments that must operate in vacuum could be used there.

One potential problem area that did not fit into any of the three categories, but was recognized as a serious difficulty for future experiments, was the contamination potential for instruments to be carried on the Shuttle. Reports of the amounts and types of materials to be dumped daily from the Shuttle indicate a serious problem with any radiometric sensor unless that sensor is protected during its entire time on the Shuttle, and then separated from the Shuttle under free flight. A complete set of specifications of materials and quantities to be dumped from the Shuttle was not available for the Panel, and they felt that such a specification should be produced or made available as soon as possible to evaluate this problem.

Electromechanical Subsystems Panel Summary

The Electromechanical Subsystems Panel recommended two major areas of improvements for use of existing space technology. A major recommendation was to utilize magnetic bearings that have already been developed in a flight test for either a scanner mirror or a nutation damper. The Panel felt that the magnetic bearings have been developed to the point where they are ready for spaceflight, but they have not been used because of institutional inertia rather than any technical problem.

Also, under the area of improvements and use of existing technology, the Panel felt that a comparative evaluation is needed of signal and power transfer devices for use in space. Low noise, high reliability devices are needed to transfer signals through rotating components and, in light of the Seasat experience, some improvement is certainly necessary in the area of transferring power through rotating components.

Under the area of development of new technology, the Electromechanical Subsystems Panel recommended several new developments. Recognizing that magnetic bearings could not be the answer to all problems, they recommended that devices be developed to force-feed lubricate bearings in space, and that sensors be developed to determine the need for such lubrication. Present sensors, such as microphonic devices or temperature sensing devices, are inadequate since the bearing will have been damaged beyond salvation by the time these devices indicate that lubrication is necessary.

In the area of servo devices, the Panel recommended that magnetic suspension be utilized to achieve accuracies of less than one arc second for scan-to-ray encoders. This is somewhat akin to the utilization of magnetic bearings, but is a new use of that technology in the area of servo encoders.

Another new technology area necessitated by the probability of recovery of spacecraft by the Shuttle is the development of the universal deployment and the retraction mechanism for use with larger arrays. A number of deployment mechanisms have been devised for deploying larger arrays; however, none have ever been required to retract those arrays as will be required if a device is to be captured by the Shuttle and brought back to Earth. In light of the large number of sizeable devices that will be deployed from Shuttle-launched spacecraft, the Panel felt that it would be economical and feasible to develop a universal deployment mechanism.

Another area that the Electromechanical Subsystems Panel recommended for development and test was that of cryogenic devices. A number of new experiments planned for Shuttle launch and operational use in the 1980's will require operation at cryogenic temperatures. Devices are needed to produce such temperatures for long periods of time such as those used on operational satellites. Technology is needed in several areas such as superconducting motors, control devices, and actuators. Suspension devices and thermal switches have not yet been developed. If experiments at cryogenic temperatures are to be continued, these developments are urgently needed.

Power Subsystems Panel Summary

Under the area of new technology developments, the Power Subsystems Panel recommended several areas of critical importance. The first area dealt with AC modeling of components for use in spacecraft power systems. They emphasized that, although some data is available on the AC performance of individual components, it is completely inadequate. Furthermore, there is very little data available on the performance of systems, and that such a system study is necessary in order to improve reliability in future spacecraft power systems.

Also, under new technology, the Power Subsystems Panel noted that new diagnostic devices are needed to determine the health of the power systems on spacecraft. Such devices are discussed in detail in their report, and include such things as devices to measure the depth of discharge of batteries.

It was noted that the requirements for increasing power on new and larger spacecraft are incompatible with the present 28 volt bus system now in use. If spacecraft power is to be increased, spacecraft power busses will have to increase in voltages to the range of 150, 300, and 500 volts. The Panel noted that there are no space-qualified components available such as capacitors, semi-conductors, switches, and relays in those voltage ranges. To raise the total spacecraft power without raising the bus voltage would give rise to unacceptable current requirements on the spacecraft power system.

Another area where new technology was considered necessary was in the area of high voltages (those exceeding 1000 volts). In this area, there have been a considerable number of failures and the Panel felt that, not only is new component design necessary, but a Design Guide Handbook, including screening and testing technique specification, is necessary to eliminate repetition of the same errors by different users of high voltages on spacecraft.

Under the area of improvement of existing technology, the Panel felt that vastly improved on-board monitoring of power systems, including mechanisms to automatically protect power systems when not in view of tracking stations, is necessary in order to increase reliability. These systems would automatically carry out emergency bypass or shutdown procedures to protect the spacecraft in the event of a failure in the power system when not being monitored by a ground control station.

It was also noted by the Power Subsystems Panel that solar cell contacts and interconnections between solar cells on spacecraft have not been as reliable as desired and that with the probability of much larger solar arrays, new methods for testing the integrity of interconnections are needed and should be developed before such arrays are launched.

Nickel-cadmium batteries have proven to be inconsistent in their performance in space and, since we will apparently be relying on such batteries for long periods of time, the Panel felt that improvement in the quality of these batteries is necessary. They suspect that problems are due to processing and processing control, and feel that improvement is necessary in both of those areas to improve the reliability of nickel-cadmium batteries.

Another problem identified was the effect of the charge buildup on spacecraft due to the substorm plasma and the necessity to understand the energy profile, and how the charge will be dissipated in spacecraft systems. Studies in this area are already underway at NASA Lewis Research Center and the Panel recommended that they be continued so that failures due to substorm plasma effects can be eliminated from future spacecraft.

Attitude Control and Determination Panel Summary

The Attitude Control and Determination Panel recommended several areas under the heading of new technology. The first area is the development of control instrumentation for on-board diagnostics and self-testing instruments for improved structural positioning and rate sensing determination. They also identified large momentum exchange devices as an area in which new technology will be required in a larger spacecraft in the future. Scaling of the presently used devices up to a larger size will carry high penalties. Without such technology, in the fairly near future, such devices could become pacing items in the launch of a larger spacecraft.

Another new technology area identified is that of automated rendezvous and docking. This technology will be necessary to carry out such operations as unmanned logistics supply, planetary sample return, asteroid capture, and assemblies of structures in space. It should be noted that this automatic rendezvous and docking does not carry with it the complexity of that involved with manned rendezvous and docking since there is not a need for a pressure-tight seal or container through which men can move. Docking may be carried out by such a simple device as magnetically coupling one structure to another; but in any event, such techniques will be necessary for missions of the type mentioned above.

In the area of technology improvement, the Attitude Control and Determination Panel recommended improvement of techniques for integrating of the control, the structure, and the dynamic design of spacecraft, especially for large space structures. This is necessary since a control or attitude determination device on one part of a large space structure may not be valid for another part due to flexure between the various components of a large space structure.

They also recommended the improvement of high performance, moderate cost and long life attitude and rate sensors. This area includes solid state star trackers to replace the presently used image dissector tubes. The solid state star tracker would provide much better reliability than the image dissector which requires high voltage for operation, and would provide accuracies to sub-arc seconds that are not achievable with the present image dissector devices.

They also recommended, under the category of improvements, assessments of non-conventional gyroscopes that have already been developed for other purposes as having potential for spaceflight use. This area could also be included under Recommendation and Policy Change, since it appears that further funding will not significantly advance the state-of-the-art with conventional gyroscopes so that a commitment is necessary to go to non-conventional gyroscopes for further improvement in this type of device.

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CHAPTER 2
REPORT OF OPTICAL RADIOMETRIC INSTRUMENTS AND CALIBRATION PANEL

INTRODUCTION

In the Flight Technology Improvement Workshop, 16 panel members made informal presentations of their recent experiences in the calibration and use of flight data from electro-optical remote sensors in a wide range of applications and made recommendations for technology improvements to enhance future applications. These presentations were, in some cases, based on informal papers submitted for review by the panel members prior to the workshop.

A general panel discussion was held which included the measurement and accuracy needs for future missions and how these new requirements would impact the recommendations based on past experience. This discussion surfaced three general problem areas in the field of radiometric instrumentation and calibration which would form the substance of the panel's deliberations. These problem areas included:

- Knowledge of in-orbit radiometric accuracy of current and past measurements is poor even where adequate calibration standards exist
- New program requirements exceed state-of-the-art for components, calibration sources and transfer standards by significant factors
- Problems encountered in past programs have revealed inadequate pre-flight ground simulation, testing, and/or modeling which simulated in-orbit flight conditions

The available standards and techniques (ground based) and required accuracy (ground based and orbital) of remote measurements are summarized in Table 1. From these discussions and considerations a wide range of technology improvement needs were identified which will be addressed in the following sections.

TABLE 1

STANDARDS AND CALIBRATION TECHNIQUES AVAILABLE AND REQUIRED ACCURACY OF REMOTE MEASUREMENTS

Spectral Range (µm)	Available Accuracy (%)	Required Accuracy (%)	Applications
0.12-0.2	25	1-5	Ozone Monitoring, Solar Variability
0.2 -0.4	10	1	
0.4 -1.6	5	0.5	Earth Resources Monitoring, Meteorology, Air Quality, Ocean Content, Hydrology, Ozone Monitoring
1.6-5.0	5	1	Earth Resources Monitoring, Meteorology, Air Quality, Ocean Content, Hydrology, Sea Surface Temp., Solar Variability
5.0-20	1	0.1-1	Sea Surface Temperature, Earth Resources, Meteorology
Integrated Broad-Band			
0.2-5.0 µm	10	0.5	Climate Monitoring
5-100	5	1	Earth Radiation Budget
0.2-100	0.5	0.1	

TECHNOLOGY DEVELOPMENT PROBLEM AREAS

Interaction with the National Bureau of Standards

Recommendations

The National Bureau of Standards (NBS) should be tasked and supported to establish, when necessary, and maintain national radiometric standards for verification of remotely sensed data applied to environmental monitoring--for at least one 22-year cycle. NBS should be tasked and supported, together with user agencies, e.g., NASA, NOAA, and EPA, to develop highly stable radiometric instruments at user facilities to allow frequent comparison of secondary standards with the primary standard.

NBS should work with user agencies to develop techniques for transfer of calibration from the national radiometric standards to particular radiometric sensors on a consultive fee basis. Application examples include:

1) Climate measurements, albedo change, etc.
2) Atmospheric constituent changes, e.g., ozone and CO_2.
3) Solar total and spectral irradiance monitoring.

Interagency/Intercenter Coordination

Recommendations

Recommendations for upgrading NASA expertise are:

1) Maintain radiometric measurement expertise at each NASA center that has radiometric sensor responsibility. Coordinate, using an OAST interagency working group. Manage, using a radiometric measurement Unique Project Number under OAST with individual Research and Technology Operating Plans at each center. Center groups would also be tasked and supported in response to short-term project requirements.

2) Establish and maintain NASA standards using NBS consultation. NASA standards would be maintained at selected NASA field centers and used to support NASA projects. Provide "consultation fee" support to NBS to advance the quality of NASA standards and to review as required the application of these standards. A set of national standards for remote sensing established and maintained at NBS would be used to back up these NASA standards.

3) Provide low-cost, end-to-end experiment concept and feasibility test opportunities using balloons, rockets, aircraft, and Shuttle. The experiments selected would be those missions where the radiometric performance required pushes the state-of-the-art. Could be used as a "fly-before-buy" competitive selection process for free-flying, long-term missions.

End-to-End System Analysis

Background

To obtain improved remote-sensor calibration, the instrument design must include total end-to-end system, including:

1) Flight hardware design including data processing.
2) Ground test equipment.
3) Calibration equipment and facilities.
4) Pre-flight test program and objectives.
5) Flight data reduction algorithms.
6) Test data reduction algorithms.

Justification

Radiometric accuracies of 3% or better require early identification of critical instrument parameters, of available primary and transfer standards for calibration, and of the test program requirements and associated test equipment to prevent bad surprises late in development. Also, sensor system and test program outputs must meet needs of flight data algorithm to facilitate efficient and timely flight data reduction.

Recommendation

NASA management should stress early end-to-end systems analysis.

Shuttle Contamination Potential

Background

A number of radiometric instruments flown on past missions have experienced in-orbit performance degradation which is known or believed to have been caused by contamination. These include ITOS, Nimbus, Landsat, CMP, and DMSP missions. Sensors with cooled optical elements and/or detectors, radiative coolers, or thermal control are particularly susceptible, since gaseous contaminants are quickly condensed on the cooled elements. This changes their transmission and/or spectral characteristics or degrades cooler efficiency and detector responsivity. Scattering or emission of energy by particles, whether on optical elements or in the field-of-view, degrades the out-of-field rejection of sensors and introduces erroneous inputs.

Justification

Optical systems not only measure the desired phenomenon but any intervening radiation between the instrument and the desired phenomenon. Therefore, it is vitally important to reduce any corrupting radiation from optics contamination to an absolute minimum. Numerous NASA and DOD experiments such as C System on DMSP, Filter-Wedge Spectrometer on Nimbus 4, Block 5A line scanner on DMSP, Very-High-Resolution Radiometer on ITOS, Surface-Composition Mapping Radiometer on Nimbus 5, and Multispectral Scanner (MSS) on Landsat 1 have been moderately to severely affected due to contamination within the measurement environment. Current NASA and DOD payloads such as Infrared Astronomical Sensor (IRAS), Shuttle Infrared Test Facility (SIRTF), and Satellite Infrared Sensor (SIRS) are all much more susceptible to contamination due to their sensitivity and out-of-field-of-view rejection requirement than any previously flown sensors.

Since most future space missions will use Shuttle as the sensor platform, the cleanliness of Shuttle will be critical to experiment success. Studies by optical-sensor engineers of the Shuttle contamination sources have led to extreme concern about using it as a sensor platform. Incomplete specifications appear to have been placed on surface cleanliness, outgassing of Shuttle materials, and contamination by waste from the onboard systems. An early Shuttle experiment on cleanliness has been planned, but there is considerable apprehension about the ability of this experiment to measure the levels, types, and distances from the Shuttle of the contaminants required by optical engineers. This has led this Panel to recommend that an immediate review of Shuttle contamination and its effects on optical sensors be accomplished.

Approach

Conduct a study dedicated to inventorying the materials and consumables employed by Shuttle and the contamination buildup likely during fabrication, testing, transportation, etc., and evaluation of the in-orbit environment resulting from this contamination, outgassing, and release of wastes, consumables, etc. The study should address the various payload configurations, be based on other similar studies which have been completed or are underway, and should evaluate the applicability of results from currently planned Shuttle Contamination Experiments for guidance in designing future remote sensors. The contaminants which are identified should be evaluated as to their effects on radiometric systems, components, and in-orbit performance.

Recommendation

A comprehensive evaluation of the Shuttle contamination environment must be made, and its effects on radiometric systems and accuracy assessed. This evaluation must address both particulate and gaseous contamination.

In-Orbit Performance of Previously Flown Remote Sensors

Background

Significant changes in radiometric response and/or calibration have been observed during space missions with several instruments such as BUV, ERB 6 and 7, and MSS, which have flown aboard several spacecraft. While some of the observed changes have been explained (e.g., BUV diffuser contamination) and avoided on subsequent missions, there are no satisfactory explanations for others (e.g., ERB 7 solar channels 6 through 9).

Justification

Measurement requirements for planned Climate and Solar Monitoring related missions impose increasingly more severe accuracy and stability criteria on planned and future radiometric systems. A compilation of past history covering a range of sensors and a correlation of observed changes with wavelength, materials, environment, etc., will be of significant value to radiometric sensor designers and evaluators.

Approach

A study should be commissioned to compile performance and descriptive data on remote sensors flown on past NASA and NOAA spacecraft which have exhibited apparent in-orbit changes of radiometric performance. Scope of the study should include data on pre-launch calibration, and on instrumentation, auxiliary measurements, etc., used to evaluate in-orbit performance in addition to configuration of the sensor hardware.

Recommendation

A study is needed to compile a history of changes of responsivity/ calibration during past flight missions and to attempt classification of observed degradation with environmental exposure and/or optical materials, electronics, detectors, coolers, etc.

Calibration Standards

Justification

A radiometric accuracy 10 times greater than currently achieved is necessary to meet remote sensing requirements, which requires:

1) Improved transfer capability from national standards.
2) Working standards that are usable in simulated and natural space environment.

This high accuracy is essential for detecting small but significant changes over long periods of time in environmental parameters. Current capabilities vs. requirements as a function of spectral region are shown in Table 1.

Approach

Support establishment and maintenance of improved standards:

1) National radiometric standards.
2) NASA working standards -- integrating spheres and solar simulators.

Support development of improved calibration transfer techniques and instruments:

1) Self-study manual documenting principles and techniques.
2) Instruments accommodating large differences in:
    a) Field-of-view, area, polarization, and spectrum.
    b) Environmental parameters and vacuum/air.

Recommendations

Develop improved primary standards as required to establish a complete set of National Standards for Remote Sensing at NBS which covers the spectral range from 0.12 micrometers to beyond 50 micrometers.

Develop NASA Calibration Standards to meet NASA program requirements and permit sensor-system calibration to required accuracy under realistic measurement conditions. This activity must include joint NASA/NBS activities to apply existing primary standards to systems test activities without unacceptable loss of accuracy.

In-Flight Calibration References

Background

To verify the calibration in orbit, a number of sensors have incorporated internal radiometric reference sources. The most stable and consistent to date have been sources for thermal IR channels using temperature monitored or controlled blackbodies. Major problems have been encountered with calibration lamps for the shorter wavelengths because of filament aging with use; tendency for heated filaments to creep or move, thus changing the efficiency of the calibration source; and susceptibility of envelope or focusing optics to contamination. Several sensors have employed diffuser plates for indirect solar viewing as an in-orbit calibration. Diffuser-plate coatings have shown changes with time due to solar UV impingements and to contamination, or combinations thereof. Conventional diffuser-plate outputs are also sensitive to illumination and/or viewing angles which introduce additional uncertainties.

Justification

The advent of the Shuttle as a measurement platform presents a critical problem from the standpoint of sensor contamination by the spacecraft environment. Knowledge of the degradation that results from this contamination is vitally important. The magnitude of the degradation is measurable using in-flight calibration sources. However, if the calibration source is not stable, then the amount of performance degradation becomes uncertain. Current in-flight sources are not adequate for monitoring these degradations. Extended mission lifetimes compound the problem and further justify the need for stable sources.

Approach

Suggested measures to improve in-flight calibration are:

1) Qualify on-board calibration sources with life tests.

2) Investigate contamination, degradation characteristics, and stability of diffuser plates.

3) Develop new and improved calibration lamps.

4) Investigate new and improved materials and techniques for in-orbit solar reference.

Recommendation

Develop in-flight reference sources to monitor radiometer instrument performance and responsivity in orbit, for use at all wavelengths from the near UV to LWIR.

High-Attenuation Neutral-Density Filters

Background

In the calibration of low-background, high-sensitivity IR radiometers such as IRAS, SIRTF, COBE, and CLIR, standard blackbody sources operating at 500K are typically employed against a room temperature (approximately 300K) background, and the input to the sensor is attenuated by several orders of magnitude, using neutral-density filters to represent the expected space measurement conditions. The uncertainties in knowledge of the spectral flatness and attenuation characteristics of the filter over the required spectral range and in the entrapment of scene energy reflected from the filter face limit calibration accuracy to 20-30% currently.

Justification

The calibration accuracies attainable for low-background, long-wavelength IR sensors are significantly poorer than those achieved for sensors making measurements of average Earth background levels and temperatures. To facilitate laboratory test and calibration of remote sensors for measuring astronomical parameters and diurnal atmospheric-constituent surveys, very low-transmission, neutral-density filters having known characteristics within 1-5% accuracy will be required.

Approach

Develop improved filters which are spectrally flat, with high attenuation across broad ranges of the IR spectrum; and develop improved laboratory facilities to characterize such filters to approximately 1% accuracy.

Recommendation

Develop improved high-attenuation neutral-density filters for use in calibrating low-background, very-high sensitivity radiometric instruments.

Solar Testing Facility

Background

While laboratory procedures using stabilized lasers as stimuli provide valuable complementary information on the properties of instrument components (e.g., the reflectance of cavity sensors), definitive testing of pyrheliometers must be performed using the Sun as a source. Use of the Sun may be more advantageous for more accurate calibration of solar occultation sensors, such as HALOE and SER, which are now being developed. The advantages are that the spectral distribution, total irradiance level, and solid angular subtense of the irradiance are close to that of the Sun in space, which is the source that the instrument is designed to measure.

Justification

Characterization and comparison of solar measurement instrumentation using the Sun as a source provide a definitive verification of accuracy in realization of SI units; correlation of results from different flight experiments; and demonstration of pre-to-post-flight performance for flight sensors.

Approach

With the addition of vacuum chamber capability, the existing building, structures, and solar tracker at the NASA/JPL facility at Table Mountain, CA will meet the basic requirements.

Recommendations

Develop a solar testing facility for multi-project use to characterize instrumentation and provide systems test capability using the Sun as a radiance source. The facility should be obtained by modification of the existing JPL Table Mountain Test Site in California.

Systems Calibration Facility

Background

NASA has generally provided test equipment, facilities, procedures, etc., as a part of the specific project development, with limited carryover and use of equipment previously developed. DOD has established calibration and test facilities at Arnold, Naval Ocean Systems Center, and at McDonald-Douglas Corporation, which have received wide use with successive generations of flight sensors of a similar type and application. With the repetitive flights required by NASA to obtain climate-type data, it will be more efficient to establish a facility at a selected location to assure "normalized" calibrations.

Justification

To meet the increasingly stringent accuracy requirements for data sets compiled from multiple-flight missions, improved calibration standards and transfer standards and techniques are required. Calibration activities conducted by experienced personnel supplemented by periodic verification of working standards, etc., can be most efficiently obtained by establishing a common test facility which carries out continuing calibrations and tests, as required.

Approach

A facility capable of providing 1% flight measurement accuracy and having the following characteristics is needed:

1) In scope, the facility would be similar to setups available to DOD, expanded to solar spectral range, but scaled down to NASA sensitivity requirements.
2) Sized to accommodate entire flight sensors in simulated (static) flight environment.
3) Target is of known radiometric characteristics (spatial, spectral, temporal, and polarization).
4) Traceability to NBS national standard is established periodically using transfer standard.
5) Adaptable to measurement of critical sensor parameters.
6) Contamination controlled.
7) Permanently and continually maintained; staffed with personnel skilled in critical transfer radiometric techniques.

Recommendations

Establish a dedicated test facility for each of the sensor types, e.g., ERB, Limb-Scanned IR, BUV, Solar Monitoring, etc., planned for repetitive, continuing use on flight missions in order to allow more efficient and more complete testing of flight systems.

Analytical Design Tools for Stray-Light

Background

Currently planned and future space-flight radiometers, such as those for the Earth radiation budget, are required to have absolute accuracies and precisions on the order of 1% and 0.1%. These radiometers are often carried on "bus" satellites which are comprised of several experiments, antennas, solar panels, etc., and consequently constitute potential out-of-field scatterers and/or emitters of energy. Early determination of instrument parameters critical to characterizing sensor field-of-view and out-of-field rejection are necessary to achieve the required accuracies within reasonable cost and schedule. Analytical programs, e.g., GURAP (General Unwanted Radiation Analysis Program), are available; however, they are cumbersome to use and terribly expensive to execute. For these reasons, a number of sensors have required design modifications during the testing phases to eliminate experimentally detected out-of-field response which had not been predicted during the design phase. Other sensors have exhibited "stray-light" problems during flight missions.

Justification

The Climate and Earth Radiation Budget experiments are currently establishing radiometric requirements an order of magnitude beyond those achieved to date. These requirements include data over long time durations requiring multiple flight missions. The sensors are flown on operational satellites to minimize cost, and these platforms (e.g., TIROS-N) have many sources of stray radiation, such as antennas, which will compromise both precision and accuracy. The use of Shuttle as a measurement platform will pose multiple stray-light problems, both from the airframe structure and other payload elements, and from particle scattering from the contaminated environment. Far infrared astronomical and DOD sensors will be particularly sensitive to these sources as well as to energy from the Earth, Sun, and other bright out-of-field sources. In summary, currently planned missions will require better understanding of, and designs for, rejection of stray radiation.

Approach

Existing analytical unwanted-radiation programs should be validated from an optical standpoint and should be modified to improve computing efficiency and reduce user cost. Their ability to handle diffraction effects must be improved.

Recommendations

Develop improved analytical design tools to assure adequate rejection of out-of-field-of-view energy (stray-light) with electro-optical system designs for use under conditions of strong backgrounds.

Systems Level Stray-Light Test Facilities

Background

The stray-light testing of sensors has historically been handled by each project individually as a part of test and calibration. This limits the funds available for test equipment, etc., and has limited tests and test conditions severely. DOD has attempted to provide a more complete capability for multiple IR sensor use at Arnold. NASA earlier had established a visible, near IR facility at General Electric for the OAO star trackers where severe requirements existed. Increasing accuracy requirements for NASA sensors will require that much improved test facilities again be developed.

Justification

The increasing need for high-accuracy sensors which operate in the presence of out-of-field rejection. (See also recommendation for improved analytical design tools).

Approach

Develop dedicated facilities for multi-project use to determine experimentally sensor-system sensitivity to stray-light. Separate facility may be required for visible near IR spectral regions and another for thermal and longwave IR spectral regions. Facilities will largely use components and techniques currently within state-of-the-art, however, and must be configured to allow efficient testing of remote sensor systems under anticipated viewing conditions. Current capabilities to measure specifically the bidirectional reflectance distribution function of materials, surfaces, cavities, etc., must be extended to small angles both to provide sensor design information and to allow validation of system level test facilities.

Recommendation

Develop facilities for experimental determination of the out-of-field-of-view rejection of remote sensor systems.

Spectrally Flat Detectors

Background

The ERBE program has specific scientific requirements for flight detectors which have the following parameters:

1) Spectral response uniform to within ± 1% over the range of 0.2 to 50 mm (this can be practically achieved only with an absorptivity of 93% over the spectral range).
2) Fields-of-view up to 150 degrees
3) Minimum sensitivity to degradation by environmental contamination.
4) Sensitivity up to $D^* = 3 \times 10^8$ cm-Hz$^{1/2}$-watt^{-1}.
5) Response time constants as short as 10 milliseconds.

For ERBE and other broadband spectral instruments, the weak link in the calibration chain is the short-wavelength calibration for wide fields-of-view. In the absence of a spectrally flat transfer standard detector, long-wavelength radiation cannot be equated with short wavelength radiation, and we must depend on a long and tenuous radiometric traceability path of transfer standard radiometer measurements of white coated reflective plates which reflect uncertain tungsten or xenon arc lamp sources, to either the World Radiometric Reference or the International Practical Temperature Scale.

Justification

Previously used flat plate thermopile, thermistor, and pyroelectric sensors have shown deficiencies in all the above-mentioned requirements and probably will not meet ERBE requirements.

Secondly, if an *electrically-calibrated*, wide-field radiometer, having greater than 99% absorptivity and uniform spectral responsivity from 0.2 to 50 mm could be developed, such a radiometer could accurately characterize the existance of a short-wavelength reflective plate on an absolute basis without requiring long and tenuous radiometric traceability to either the World Radiometric Reference or the International Practical Temperature Scale.

Approach

Develop a family of active and/or passive cavity sensors whose designs are optimized for specific measurement requirements.

This development should yield detectors for ERBE flight instruments as well as transfer standard radiometers for use in absolute radiometric calibration at *all* wavelengths, thus addressing deficiencies in the general calibration areas.

Recommendation

Develop a family of spectrally flat, high-absorptance, wide field-of-view sensitive detectors having a true cosine response for use in flight sensors and in the laboratory.

Long-Term Stability Sensor Components

Background

Some components degrade with time in an unknown manner resulting in uncertain instrument accuracy. Examples of component degradation include:

1) Blue haze on super-polished mirrors.

2) Severe degradation in orbit of solar attenuators on BUV and ERB due to solar UV and other environmental factors.

3) Suprasil changes on ERBS 6 due to UV.

4) Degradation, spectral shifts, out-of-band transmission, and excess scattering for spectral filters and coatings.

Justification

Extended operation in space and some observed degradation have resulted in uncertain instrument accuracy. New planned programs demand even greater accuracy and, in some cases, even longer duration missions. The problem of stability verification of self-calibrating radiometers to the 0.1% relative accuracy level is extremely difficult and requires development of new technology and techniques to realize the total of 1.0% accuracy of data over a 22-year period. The establishment of long-term stability of the radiometers used in the Solar Monitoring Program is critical for the success of the program.

Approach

Investigate changes with widely-used material and components, develop new improved components and materials that match new system requirements, and provide long-term stability in orbital performance. The following Table lists a number of components which need early study and consideration.

TABLE 2 - Required Component Developments

Component	Problem	Recommendation
Onboard calib. source	Long-term stability	Qualify with life tests
Reference solar diffuser	Unknown in-orbit degradation	Investigate contamination and stability
Suprasil optics	In-orbit degradation	Investigate and characterize
Very low scatter mirrors	"Blue haze" phenomenon	Investigate and control
Spectral filters and coatings	Degradation, spectral shifts, out-of-band transmission, and excess scattering	Develop better filters
Detectors and preamplifiers	Stability and linearity over very large dynamic range	Develop for new program requirements

Recommendation

Investigate long-term stability of optical components, spectral filters, detectors, and in-flight reference sources under typical laboratory and space flight environments to increase accuracy and minimize in-orbit degradation of future sensor systems.

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

As a result of the workshop, a number of conclusions were reached, some of which assess the current radiometric-sensor state-of-the-art vs. requirements, some that indicate NASA should make changes in policy and procedures to facilitate improved communication and interactions with other government agencies and between NASA centers, and some detailed conclusions and recommendations as to needed improvements in technology. These conclusions are summarized as follows:

NASA Policy and/or Procedural Changes

1) A standing interagency and intercenter committee should be established to maintain cognizance of radiometric calibration requirements, capabilities, and new technology needs within NASA and NBS. DOD and NOAA members may also be desirable.

2) A centralized radiometric measurement and calibration expertise group should be developed and maintained at each NASA center responsible for radiometric sensor development and application. These expertise groups would be individually supported by the Office of Aeronautical and Space Technology (OAST) and would be responsible for assuring the proper application of calibration standards to each remote sensor system. They should each be represented on the interagency standing committee, which would coordinate their activities.

3) NBS should be supported and charged with establishing and maintaining a set of National Standards for Remote Sensing as a primary base for calibrations of all sensors.

4) NASA Calibration Standards should be established at selected NASA centers to support remote measurement projects. These standards would be developed by NBS and/or NASA, with "consultation fee" support provided to NBS for its development, improvement, and periodic verification. Similar NBS support would be required to help establish procedures and techniques for applying NASA Standards to specific systems. For this latter purpose, the committee feels NASA should support further development of the NBS Self-Study Manual on Optical Radiation Measurements (NBS Technical Series) as reference material.

5) NASA should consider a program to provide more accessible "low-cost" flight opportunities for feasibility and "end-to-end" testing of measurement concepts, instrumentation, and software prior to committal to long-term, free-flyer missions. Balloons, aircraft, rockets, or Shuttle would be used to verify performance of systems requiring significant advances in radiometric state-of-the-art before undertaking development of more expensive long-term Class A or B missions.

6) NASA program and project management should stress the use of "end-to-end" system analysis and design early in the design phase of radiometric

system development. This effort would include all measurement aspects from the observed source characteristics and sensor environment through the data reduction requirements for ground-test and flight data. Pre-launch ground testing and calibration should realistically simulate flight measurement conditions and environment for maximum confidence and accuracy.

Needed Improvements in Technology

1) A much-improved knowledge of the Shuttle contamination environment and an evaluation of its potential impact on radiometric sensors is urgently needed.

2) Compilation and analysis of data from past missions which exhibited evidence of in-orbit calibration changes or performance degradation will provide valuable design data and criteria for future development of more accurate radiometric instruments.

3) Primary radiance and irradiance standards currently available for radiometric calibration are not adequate to meet requirements for planned and future missions. Accuracy limitations are most severe in the short-wavelength region (≤ 5 μm).

4) Much improved calibration transfer standards and techniques are required to take advantage of existing primary standards and obtain improved calibration accuracy for remote sensor systems.

5) Improved in-flight calibration sources are required to monitor in-orbit performance of remote sensors. As with primary standards, present accuracy is worst in short-wavelength regions.

6) High-attenuation, spectrally-flat, "neutral-density" filter technology is inadequate for calibration of low-background, low radiance-threshold sensors for astronomy and defense measurements.

7) A facility is badly needed to allow ground calibration of pyrheliometers and solar occultation sensors while operating in a vacuum environment and viewing the solar disc.

8) Dedicated calibration facilities should be established for each of the remote-sensor types or categories (e.g., Earth radiation budget or solar monitoring) which are planned for continuing applications. Such facilities would permit more efficient and more complete testing and calibration of each of the sensors while providing traceability of the multiple calibrations to reference standards.

9) More efficient analytical design tools to evaluate the out-of-field-of-view rejection ("stray-light" sensitivity) for remote-sensor optical systems are badly needed. Lack of flexibility and high computer costs limit use of currently available tools during the design phase. This often leads to expensive redesign late in the program and occasionally compromises in-orbit performance.

10) Development of a dedicated facility to permit experimental evaluation of remote-sensor "stray-light" sensitivity would allow more complete testing and probably reduce costs for NASA-wide sensor testing.

11) The development of a family of wide-angle, spectrally-flat, "self-calibrating" detectors is urgently needed for both flight and laboratory applications. They would allow much improved flight measurements for Earth-radiation budget and other climate-related applications. These detectors will also facilitate the development of calibration transfer techniques and standards for laboratory calibrations of sensor systems.

12) The stability of the spectral, transmission, reflection, and scattering characteristics of state-of-the-art optical elements including mirrors, filters, etc., must be investigated to provide design and testing criteria for future remote sensors of higher radiometric accuracy and performance.

Radiometric Needs Versus State-of-the-Art

1) Measurement requirements imposed by the planned climate-related flight missions include radiometric accuracy and stability which is improved more than one order at magnitude over current experience. This is particularly true for Earth radiation budget parameters requiring very high accuracy to relate data obtained over long time spans ($\geq$ 22 years) and from multiple flight missions.

2) Experience indicates that our knowledge of the in-orbit radiometric accuracy obtained from past missions is poor, even where adequate primary calibration standards are available. A primary contributor to this fact has been inadequate pre-flight ground simulation, testing, and/or modeling of the sensors to represent realistically the in-orbit measurement and environmental conditions. Another factor has been use of inadequate calibration transfer standards and/or techniques to interface the sensors with available primary standards during ground calibration.

3) Requirements for low-radiance threshold measurements for astronomy and for defense-related parameters impose a need for much improved sensor design, calibration, and testing procedures and facilities. Currently, uncertainties in laboratory calibration over large dynamic ranges and low background conditions, and in the knowledge of sensor rejection of unwanted off-axis radiation during flight, are believed to be the limiting factors.

4) In-orbit performance degradation caused by contamination of sensor system optics by space platform environments is a major problem in obtaining high radiometric accuracy over extended mission lifetimes. Current in-flight calibration monitors are not adequate for accurately assessing this degradation. The contamination problem will become particularly severe with the use of Shuttle as a measurement platform, even with its use as a launcher for free-flyer spacecraft. Sensor systems which employ cooled optical components and/or detectors are particularly susceptible, and gaseous contaminants will be rapidly condensed onto the cooled components, thus affecting performance and calibration.

PRIORITIZED RECOMMENDATIONS FOR IMPROVED RADIOMETRIC INSTRUMENTS

The panel obviously felt that all of the needs reflected by the conclusions are real and should be pursued; however, the following recommendations are believed to be of widest and most valuable near-term usefulness:

1) Establish the interagency/intercenter committee to coordinate calibration requirements.
2) Establish National Standards for Remote Sensing through NBS support.
3) Establish NASA Calibration Standards and calibration transfer techniques through joint NASA/NBS developments.
4) Conduct a study to define the Shuttle contamination environment.
5) Develop a family of wide-angle, spectrally-flat detectors.
6) Investigate stability of state-of-the-art radiometric components.

CHAPTER 3
REPORT OF THE ELECTROMECHANICAL SUBSYSTEMS PANEL

INTRODUCTION

The Electromechanical Subsystems Panel began the deliberations with summary presentations of papers previously submitted by some of the panel members. Presentations were made as follows:

1) Philip A. Studer, "Plus and Minus 90°". - This was a summary of flight anomalies of the past 20 years in space (covering 350 spacecraft from 52 different programs) in addition to a review of malfunction reports as guides to future development needs.

2) Walter R. McIntosh, "Star Tracker Sensors for Space Applications". This paper discussed the need for a solid state CCD or CID device customized for star tracker application to circumvent corona problems with the present high voltage image dissectors.

3) Derek Binge, "Mechanisms for the Deployment of Space Structures". - This paper identified troublesome areas in devices such as latches, dampers, position sensors, and others which are used for deployment and retraction.

4) Peter E. Jacobson, "Rotating Electrical Circuit Interface Failures - Slip Ring/Brush Sets Compared to an Advanced Roll-Ring Configuration". This paper identified a new arcing failure mechanism associated with minute debris particles and indicated that the development of roll-ring technology has advanced to a point of being a viable alternative to the slip ring/brush.

5) George Zaremba, "New Stepper Motor Drive Technology Circumvents a Different Servo Controller Problem". This paper described a new pointing subsystem development with biaxial capability to stably point an instrument to within 5 arc sec total error.

6) Capt. Howard J. Mitchell, "Lazarus Sleeps No More". This paper described the unique analysis and control techniques used to recover the first Defense Meteorological Satellite Program (DMSP) Block 5D satellite which had tumbled out of control shortly after launch.

7) Tom Flatley, "Counterspun Compliant Flywheel Nutation Damper". - This paper described a unique nutation damper invented by S. Tonkin of England which may provide a simple, reliable approach for short-term nutation control, such as in sounding rocket flights and for Solid Spinning Upper Stage (SSUS).

The paper by Mr. Flatley on the Tonkin nutation damper was presented to this panel for information only, since the subject matter was assigned to the Attitude Control and Determination Panel.

On the second day of the Workshop, the Panel discussed past and present deficiencies and new requirements to identify the drivers for what new developments are needed. In the area of deficiencies, lack of torque margin, lack of adequate dampers and insufficient accuracy were identified. In the area of new requirements, the following were among those identified:

1) Longer life, in general (for free flyers)
2) Operation over wider temperature ranges (Shuttle environment)
3) Operation in cryogenic temperatures
4) Operation after extended periods of inactivity in space (Shuttle retrieval)

These deficiencies and requirements were then viewed in terms of general classes of new developments which are needed, such as non-contacting mechanisms, dampers, hinge joints, forced lubrication devices, etc. As a result of this discussion, the following list of items evolved:

1) Magnetic bearings (need system application development)
2) Lubrication for long life
3) Improved signal transfer devices
4) Improved power transfer devices
5) Improved servo sensing devices
6) Deployment/retraction devices
7) Cryogenic devices
8) Ordnance substitute (EED's leak)
9) Data storage (replace tape recorders)

After some discussion, agreement was reached on which new developments the Panel would submit recommendations for, and which would be mentioned as items of merit for further consideration (but for which no recommendation would be offered). Writing assignments were then made as follows:

Magnetic Bearings	Chester J. Pentlicki
Lubrication	Derek Binge George Zaremba

Signal and Power Transfer Devices	Peter E. Jacobson
Servo Sensing Devices	Ron Baker George Zaremba Walter R. McIntosh Philip A. Studer
Deployment and Retraction Devices	Howard J. Mitchell
Cryogenic Devices	Philip A. Studer Richard M. Boykin
Digital Servo Electronics	Philip A. Studer

Assignments on other items of merit:

Data Storage	Bob Wilding
Ordnance Substitute	Philip A. Studer

These assignments were completed, the writeups reviewed by the Panel, and a summary presentation was prepared. The completed writing assignments, as submitted for review by the Panel membership, are included below, and constitute part of this report.

TECHNOLOGY DEVELOPMENT PROBLEM AREAS

Magnetic Bearings

Background

Future spacecraft systems are expected to have requirements for extended lifetimes and more precise pointing requirements for spacecraft as well as instrument packages. In addition, the thermal environment is expected to become more severe, reaching cryogenic temperature levels for some applications. These considerations impact on the electromechanical actuators foreseen for these future missions. Momentum wheels and gimbal systems are examples of such actuators.

The current practice is to use ballbearing suspension in the devices. The ballbearing systems have many limitations. The stiction and running torque force compromises in terms of torque margin and servoloop design. In some cases indirect drive, with its associated gearing, is chosen over the simpler direct drive to ensure adequate torque margin and accuracy. The devices are very sensitive to temperature due to lubricant characteristics as well as the tight fits required.

A method of maintaining satisfactory lubricant supply for the extended missions (10 years) has not yet been achieved. Modeling of the lubrication system lags far behind application with consequential risks. Bearing performance is frequently, especially for higher speed devices, difficult to predict. Bearing cage instability has occurred with distressing frequency. The actuators considered here are often critical to the spacecraft success and not capable of redundant pairing. Solar array and despun antenna drives are examples. In other cases redundancy is possible, as with momentum wheels, but with weight and cost penalties. Life testing is difficult, expensive, and the results are often not timely.

Magnetic bearing systems have none of these limitations. The contactless suspension system has negligible stiction, low dynamic torque, no wearout mechanism, tolerance of extreme temperatures, and for many cases can be made sufficiently reliable to eliminate the need for redundant devices. Because of this, they have been under development for several years both in the United States and in Europe. Most of the effort has focused on incorporating magnetic bearings in momentum wheels. Several successful engineering models have been constructed, and at least one design has been flight qualified. None has yet flown. The magnetic bearing technology that has been developed has not been applied to the broader areas of devices that could profit from non-contact suspension. The progress in magnetic bearings has faltered.

Recommendations

The application of magnetic bearing technology has faltered because of institutional inertia and the perceived risk of something new. To hurdle this barrier the following steps should be taken.

1) Flight demonstration of a magnetic bearing in orbit. Whereas development of magnetic bearing momentum wheels are far along they appear to be the best candidate for a near-term demonstration. Such a demonstration is critical to achieving acceptance of this technology by program managers. The technology is available and must be moved from the laboratory to the field.

2) Apply magnetic bearing technology to solar array drives, scanning mirror suspensions, and instrument package platforms.

3) Investigate the use of magnetic suspension at cryogenic temperatures.

4) Develop magnetically suspended nutation damper.

Lubrication for Long Life

Background

Oil lubricated ball bearings are key elements in satellite rotary systems. Reaction wheels, scanning devices, and despin mechanical assemblies are examples where long life and uniform torque performance are dependent on rolling element bearings.

Maintenance of a thin, clean, and uniform lubricant film at and near the bearing EHD ball-to-race contact zones and the ball to retainer picket interfaces is essential to performance. Lubricant for this purpose can be provided by passive means during the design life as long as on-orbit conditions do not vary from the design predictions.

For long life requirements and a premature lubricant depletion from the bearing cavity, a commandable oiler to replenish the lubricant, when necessary, becomes increasingly desirable.

The basic design constraint in active oiling is to deliver all of the lubricant in a small metered charge uniformly to the ball pockets and to the contact zones of both the inner and outer races. These regions are not easily accessed. Preferably, the lubrication should be done slowly by a device which is compatible with unmodified bearings and does not introduce contamination or torque transients. The knowledge of the frequency of oiling is also an important constraint which must be determined from periodic monitoring of the shaft torque, bearing temperature, lubricant film thickness, and the payload stability criteria, if appropriate.

Review of literature indicates several design ideas for the oil applicator system. None of these, however, appears to be sufficiently developed for space usage. The indicated need and the present design status are the basic motivating factors in the recommendation of serious development of a commandable oil applicator. The scope of the developmental program should not only include the implementation of an active oiler mechanism for space flight applications, but also should consider lubricant transfer modeling of passive lubrication schemes which should retain their present status of basic replenishment sources.

Drivers

The key drivers for this technology are:

1) Continued use for conventional bearings in medium to high speed rotational mechanisms.
2) Extended operational life in excess of 8 years.
3) Operation or reoperation following extended storage or inactivity in space-retrieval.

4) Extreme thermal environments

   - Shuttle
   - Cryogenic systems coolers.

Major Areas of Application

1) Lubrication for momentum wheels, reaction wheels, scanners.
2) Lubrication systems for actuators (motors, gears, bearings) for one-shot limited duty cycle devices activated after long time storage in the space environment.
3) Tribology considerations for devices operated at cryogenic temperatures.

Rationale

The rationale for technology development includes:

1) Difficulty in assuring more than 8 years life with existing one-shot lubrication techniques.
2) No assurance that power will be available to heat actuators at end of life in orbit.
3) Self-lubricating materials must be resistant to cold flow type problems.
4) Tribology considerations for operations of mechanisms at cryogenic temperatures. Heaters are not usable on devices.

Recommendation

The recommendations of the panel include:

1) Forced feed lubrication systems for conventional bearings.
2) Develop techniques to assure a metered replenishment of oil to the bearing surfaces.
3) Develop technology and/or sensors to determine need for relubrication.
4) Develop sensors or techniques to detect reduction in oil film on bearing surfaces.
5) Lubricants or materials for use in bearings and gears compatible with the extended storage in space prior to reactivation or retrieval.
6) Materials for long life storage
   - Changes in physical properties
   - Outgassing considerations
   - Long-term storage under stress (cold flow).

7) Develop technology for mechanisms, actuators operating at cryogenic temperatures.

8) Obtain an understanding of sliding or rolling contact at cryogenic temperatures.

Signal and Power Transfer Devices

Background

As spacecraft systems become more active, higher torque margins between the driver and the various load sources are required. Tighter positional accuracy also places a stronger emphasis on reduced load torques. These existing deficiencies place new demands upon electrical transfer devices. As magnetic bearings become recognized suspension elements in future spacecraft, their inherently low and noise free torque characteristics and longer life can best be utilized if improved electrical transfer devices are developed. Increased ball bearing life will also result from improved lubrication technology and will require compatible electrical transfer improvements for these systems. New and wider operating temperature requirements also place new demands on electrical transfer devices.

Specifics

Signal transfer devices must not only be improved to correct these deficiencies listed but must also be capable of transferring greater data rates. Many new technologies now exist which should be explored in greater depth in this regard. Non-contacting signal coupling may be optical, RF, magnetic or capacitive. The optical and magnetic coupling have become, or will soon be, space qualified. The signals, which are converted to AC to be compatible with the interface are processed on either side of the interface as required. Rolling contacts provide an alternate means of signal transfer.

It is recommended that a development program be conducted consisting of an initial compilation of existing technology followed by actual brassboard testing of prime candidates. This second brassboard phase would include environmental and life testing. In the initial phase the inherent advantages and disadvantages of both contacting and non-contacting signal transfer devices would be compiled and specific risk, performance and environmental factors established. It is probable that the variety of both existing and future applications may identify more than one candidate for brassboard development and test in the second phase.

Power transfer devices must also be improved to correct the deficiencies of torque margin, positional accuracy and life and to accommodate the new temperature requirements as stated in the "Background" discussion. These improved devices must consider both magnetic suspensions and ball bearing configurations. Although it is true that new technologies exist for power transfer, some of the candidates listed for signal transfer are either not applicable or are not as mature. Magnetic power transfer coupling for instance by means of rotary transformers requires new technology development for future power requirements. Until power lasers become sufficiently mature optical power coupling is not a candidate. Although it is improbable that capacitive and RF coupling can be utilized for power transfer even at higher frequencies, they should be considered as candidates in the initial phase. In the contacting category, rolling contacts, because of other unique advantages, are another power transfer candidate.

It is recommended that a two-phase development program be conducted identical to that recommended for the improved signal transfer device. This program differs, however, from the standpoint of technology requirements since it is much less mature at this time. This technology study should not only consider power transfer candidates on the basis of risk, performance and environmental factors but power efficiency as well since a low efficiency results in undesirable thermal and power characteristics.

Servo Sensing Devices

Background

As future missions are defined, the need for more stable and more accurate servo performance requirements emerge. Past experience in the servo control area has identified the fact that a feedback servo control loop can never perform any better than its feedback sensor. In addition servo design has been compromised by and servo performance has been restricted by the presence of undesirable frictional and "spring" load torques. With the development of magnetic bearings and the application of flexural pivots, the need for sensors consistent with non-contacting technologies is amplified. The application of microprocessors to servo control loops results in the need for sensors directly compatible with microprocessor interfaces.

The recommendation is to apply funds to support the evaluation and improvement of existing sensors and development of new sensors with finer accuracy, non-contacting mechanical designs, direct microprocessor compatibility, and improved temperature range and life. Some examples follow:

Zero Ripple Torque Motor

Torque ripple is characteristic of motors, which poses some difficulties in meeting high performance servo requirements. There have been several approaches which can potentially eliminate this problem: (1) Magnetic field shaping which requires special motor design; (2) Control sensing techniques which require sensing instantaneous flux distribution (or generated voltage) and current. These approaches should be evaluated and the most universal and cost-effective solution developed and qualified.

Shaft Encoding Devices

Implementation of high accuracy pointing systems (1 to 2 arc-sec) requires displacement transducing devices capable of encoding a fraction of one arc-sec.

At the present time, there are optical encoders which can fulfill such a function. However, their geometric size, weight and excessive power consumption make them unsuitable for applications where low power and weight are the dominant constraints.

Since the basic contributor to the encoder errors is its ball bearing suspension and since it is not possible to further enhance the performance of the ball bearings, magnetically suspended encoder elements are suggested.

The developmental scope of such a device should emphasize:

- Small size and light weight
- Low power consumption
- Active correlation of the transduced signal with the measured bearing errors.

Scanned Encoder

An incremental optical shaft encoder, if equipped with an array of light source/detectors instead of a discrete readout station, would be useful at all speeds including zero and have an increased resolution by a factor of 8 to 10. A monolithic array of detectors is necessary to obtain the positional accuracy necessary to subdivide the least bit of resolution of the optical disc. Electronically scanning the detector array at a rate outside the physical rotation rate of interest would make all rate measurements relative to the (crystal controlled) scan frequency. Thus a high information rate needed for direct compatibility with digital (microprocessor) control would be obtained.

Servo Sensing Devices

The development drivers for image sensors include:

- Improved reliability
- High accuracy
- Longer life
- Multi-mission usage

One of the major problems with present star trackers is a common high voltage failure (HEAO-2 being the latest). The high voltage is necessary to operate the sensor used in the tracker, that is, the image dissector tube (IDT). Star trackers using the IDT have achieved noise-limited performance and meet most accuracy requirements of present systems. The fact that these IDT trackers have achieved noise-limited performance in effect means that star accuracy cannot be improved with an IDT. (The IDT is approximately 15 years old).

During the past several years, solid state sensor (SSS) arrays have been in the process of being developed. These arrays operate with low voltage which would eliminate the failure mode of the IDT. Analytical studies have been made that have found a number of other distinct advantages that the SSS has over the IDT:

- Higher quantum efficiency
- Magnetic field immunity
- Broader spectral response
- Greater linearity
- Digital output

However, with all the potential advantages of the SSS they are not directly applicable to star trackers. This is due primarily to the fact that the major development work on the SSS has been directed toward TV cameras. Although many of the requirements for the SSS are the same there is a major difference, that is, the method used to obtain the output. For the TV mode, elements are raster scanned with the video shifted out sequentially. For star trackers a raster scan is required until a star is detected; at this point a random access readout is desirable so that the video of the star image can be shifted out at a low rate; that is, only the elements with the star image are shifted out.

Recommendation

The recommendation made by the panel includes the need to customize a solid-state sensor with random access of data suitable for star tracker applications.

Deployment and Retraction Mechanism

The development drivers for developing technology for deployment and retraction mechanism include:

1) Past history of problems.
2) Increased usage of deployables considering launch cost and size of structures.
3) Retractability required for Shuttle.

The major areas or needs include:

1) Deployment mechanism for non-retractable devices.
2) Deployment mechanism for retractable devices.

The primary recommendation made by the panel is to develop a Standard Deployment Mechanism. This will involve the design, fabrication and testing of a Representative Deployment Mechanism considering the following variable component philosophy:

1) Variable Rate Required
    a) Damper
    b) Motors

2) Variable Torque
    a) Springs
    b) Motor

3) Type of Deployment
    a) Permanent
        i) Restraint and release mechanism
        ii) Latching mechanism
    b) Retractable
        i) Beginning and end of travel restraint
        ii) Beginning and end of travel release

4) Hinge Selectability
    a) Bearing size
    b) Shaft size

5) Lubrication Selectability
    a) Permanently deployed
    b) Retractable - long life required

6) Continuous positioning sensing

7) Other Considerations
    a) Thermal environment
    b) Launch loads
    c) Redundancy
    d) Testability of the deployable

Additional rationale for the development is that:

1) Currently no design standards exist

2) Variable design allows for tailoring to the particular application

3) Current problems can usually be traced to the deployment mechanism, not the deployable

Cryogenic Devices and Materials

Deficiency

In order to obtain increases in accuracy and sensitivity the trend in detectors is toward operation at cryogenic temperatures. This imposes new and specialized demands on materials and devices used in this environment. Problem areas include thermal expansion and contraction causing high stresses and failure, embrittlements causing failure due to thermal shock and/or fatigue, severely limiting lifetime, and binding or leakage due to material shrinkage or hardening. The lack of knowledge as to the characteristics and behavior of material at cryogenic temperatures is a major problem to the design.

The basis for the Panel's recommendations does not include any flight deficiencies since little prior flight experience exists. The requirements stem from the need for active devices, primarily scientific instruments and scanning devices, in a new environment which precludes conventional lubrication and where thermal dissipation must be kept to extremely low values (refrigeration requires 1000 W/W of dissipation).

Development Required

Methods to characterize properties of materials at cryogenic temperatures are needed. The identification or development of materials that will retain those properties at the low temperatures are needed. These materials include adhesives, lubricants, and flexible materials for seals and dynamic isolation. Devices that are needed would include actuators and control devices.

New development is required in suspension systems which require no lubrication such as flexures or magnetics. Suspension of moving elements by these means further requires caging devices to survive the launch environment. Passage of signals and power to moving devices while preserving low thermal conductivity will require non-contacting or intermittent contacts. The materials themselves need special selection due to thermal coefficient of expansion, brittleness, and conductivity requirements. For the electromagnetic devices which can take advantage of the low and zero resistance state, however, switching and control of currents is a unique problem area. The design of electromagnetic devices to make practical use of the superconducting state is still in its infancy.

Recommendation

It is recommended first that from the standpoint of materials that a test program be started to identify and characterize the properties of existing materials at cryogenic temperatures. This would provide the necessary data for the designers and would identify where deficiencies exist. A materials development program, leading to materials to satisfy the needs, could then be structured.

Basic work needs to be done on the design and control of actuators and suspension techniques at superconducting temperatures.

Cryogenic Coolers

Development Drivers

The need for lower temperatures and greater thermal load capacity than that which can be provided by small passive coolers is already being felt as larger (array) detectors become available and the need to cool the optics as well as the detectors themselves becomes apparent. Alternative approaches such as solid cryogens have obvious life limitations.

The prospects of very small low power computers of huge capacity operating at cryogenic temperatures are being evaluated.

Major Areas

Mechanical coolers exist which have the requisite thermodynamic performance but which are not capable of long term unattended operation and which impose dynamic disturbances which adversely affect the instrument application and the spacecraft. In small sizes these are reciprocating devices and need to be designed to eliminate rotary to linear conversion and sliding contact seals and bearings, and to incorporate dynamic balancing. Multiple state or combined cycle machines (e.g., mechanical and magnetic) need to be developed to extend the range of temperatures down to liquid helium.

Recommendation

It is recognized that programs are already in progress to develop the necessary technology in this area. The continuation of these developments should be supported.

Digital Servo Electronics

Deficiency

Rather than a deficiency of prior flight history, the new capability offered by digital control was amply demonstrated by the saving of the first DMSP Block 5D spacecraft by in-flight reprogramming of the entire control system. The applicability of these techniques to achieve significantly better performance in electromechanical systems was exemplified by an arc-sec stepping scanner. Reprogrammability in the Shuttle era to permit parameter changes to accommodate mission-to-mission and instrument complement changes between flights without hardware changes is crucial. While abundant attention has been paid to microprocessors and related software, the power level interface with electromagnetic actuators has seen little attention.

Development Required

The development required includes:

1) Monolithic construction and packaging of 2-phase and 3-phase power switching modules employing the latest power-FET technology and fast recovery diodes.

2) Monolithic integrated circuit decoding devices for motor commutation and stepper motor sequencing.

3) Programmable digital servo compensation circuits with feedback sensor compatibility.

Recommendation

The recommendation made by the Panel includes:

1) Evaluate currently used discrete and analog circuitry presently used for these repetitive functions.

2) Develop programmable circuits in monolithic form which provide all the essential motor control functions and qualify them as preferred parts.

3) Document and disseminate specifications and user guidelines for these devices.

Rationale

Numerous flight programs have not used current state-of-the-art technology for short term or non-mission critical applications because of cost or availability - many otherwise competent suppliers of electromechanical devices do not have electronic expertise or resources to provide these devices in any form. Flight programs for instruments and major spacecraft components expend considerable resources developing functionally identical circuitry yet, because of the low quantities in each application are often not providing the proven reliability, size, power, and performance advantages afforded by large- or medium-scale integration. The present switch to microprocessor-based systems makes this an opportune time to meet the Shuttle era's need for reprogrammability and conserve resources on many individual instrument and spacecraft programs.

The following areas were also discussed by the Panel and determined to be worthy of consideration for future technology development. However, the preceding areas are considered significantly more important than the ones that follow.

Ordnance Substitute

Deficiency

Laboratory testing has shown that pyrotechnic actuators and release mechanisms are prone to leak, especially after firing, which builds extreme internal pressures. This situation has not appreciably improved over the years and the resultant contamination is of great concern in radiometric and other sensing systems.

Development Needed

A high force lightweight electrically triggerable actuator is needed. It should be reusable to permit test verification. A candidate device is available commercially with some flight history as a magnetometer "flipper". The commercial device requires an electrical heater and special insulation for this purpose, since it is used as an automobile thermostat. Minimal development would be required to evaluate and qualify it as a release element. With some further development it potentially could provide the controlled rate deployment which is sought to eliminate leak prone viscous dampers on antenna, array, and boom deployment.

Recommendation

The recommendations include:

1) Evaluate "wax pellet" actuators for release and one-shot actuation requirements.
2) Develop rate controlled deployment and retraction actuators based on the same design concept.

Rationale

A low-cost device may be a safer, testable, and reusable alternative avoiding some of the perennial problems of explosive devices. Relatively small development might suit the same concept to other more sophisticated requirements.

Tape Transports for Data Storage

Development Drivers

The development drivers include:

1) Past flight experience in the performance of these devices has, in general, been poor. Poor performance primarily is in short life and high noise.
2) Spacecraft continued growth places a demand on increased storage capacity and redundancy.

Recommendation

There is no recommendation in the area of electromechanical new technology design. The belief of the committee is that these devices will ultimately be replaced by passive electrical devices and all new development effort should point in that direction.

SUMMARY OF RECOMMENDATIONS

The recommendations made by the panel for each of the technology deficiencies or technology problem areas are summarized in the following paragraphs.

Magnetic Bearings

1) Conduct flight demonstration of momentum wheels with magnetic bearings.

2) Apply magnetic bearing technology to scanning instruments and instrument package platforms.

3) Investigate use of magnetic suspension at cryogenic temperatures.

4) Develop magnetically suspended nutation damper.

Lubrication

1) Develop forced feed lubrication system for ball bearings.

2) Develop sensors to determine need for re-lubrication.

3) Investigate lubricants and materials for bearings and gears to be operated after extended storage in orbit, and/or operation at cryogenic temperatures.

Signal and Power Transfer Devices

1) Conduct comparative evaluation of existing technology to select candidate approaches.

2) Develop brassboards and test prime candidates.

3) Space qualify best candidates.

Servo Sensing Devices

1) Evaluate and improve existing sensors.

2) Develop new sensors, such as:

    a) Active magnetic suspension that will support an encoder with minimum runout and yield accuracies to less than an arc-second

    b) Zero ripple torque motor

    c) Encoder with scanned array

    d) Monolithic IC sensors

Deployment and Retraction Mechanisms

1) Develop universal deployment mechanism concepts.

    a) Testable in 1G environment

    b) Optimum from overall system standpoint

2) Fabricate, test and space qualify representative configurations.

Cryogenic Devices

1) Characterize materials and electronic devices at cryogenic temperatures.

2) Continue development of mechanical cooler.

3) Develop technology for operating at cryogenic temperatures.

    a) Superconducting motors and control devices

    b) Actuators and suspension devices

    c) Thermal switches

Digital Servo Electronics

1) Fabricate and qualify:

   a) Motor commutation and stepper logic circuits in monolithic form using power FET's and fast diode technology.

   b) Programmable digital servo compensation IC's with feedback sensor compatibility.

CHAPTER 4
REPORT OF THE POWER SUBSYSTEMS PANEL

INTRODUCTION

A representative cross-section of space power specialists deliberated for three days with the common objective of identifying a prioritized list of recommended technology thrusts for the NASA Office of Aeronautics and Space Technology. The group consisted of representatives from NASA, DOD, COMSAT, and industry, representing primarily the segment of the space power peer group responsible for spacecraft power system. The strategy was for each participant to bring to the meeting a paper and presentation describing specific problems encountered by his particular organization wherein technology improvement could have either avoided or minimized the problem. The thrust of these presentations were to (1) identify various problems and inadequacies in the past and ongoing spacecraft power system design, test, integration, and operation, and (2) define necessary solution(s) via supporting technology development work required. Most specific problems naturally related to past space flight experience but essentially all had merit with respect to ongoing or future planned spacecraft. Every participant entered into vigorous discussion describing in great detail specific problems, which was the primary contributing element to the highly successful meeting. After hearing all the problem details, there was very little problem establishing the prioritized list of specific recommendations with essentially no minority reports needed.

The overall approach taken in the workshop was composed of three basic steps:

1) Identify Technology Problem areas being encountered in present systems.

2) Translate the Technology Problems into Technology Development Requirements.

3) Prioritize the Technology Development Requirements to establish a basis for NASA planning and work recommendations.

The following sections describe these steps and the results obtained.

TECHNOLOGY DEVELOPMENT PROBLEM AREAS

Following the problem and recommended study-area discussions presented during the workshop, the workshop participants translated the problems into technology problem statements and listed them for consideration as needed work.

A ground rule followed was that needed work should not be identified for Advanced Systems such as Space Power Systems or large space platforms. The emphasis was placed on present and near term problems and needs. Specific direction to avoid priorities at this stage was imposed to assure full participation by the entire workshop.

The specific technology problems were posted under the following electrical power technology areas:

1) Power System
2) Solar Array
3) Battery
4) Power Distribution (switching, fault protection, cables, high voltage)
5) Power Conditioning Electronics
6) High Voltage Power Supplies
7) Power Transfer
8) General Problems (data, qualified parts, etc.)

The listing of problem areas/technology needs and needed engineering tool improvements was very large. The workshop panel then proceeded to group the problems in an attempt to combine and reduce them into viable work categories as follows:

1) Substorm and Plasma Design Data
2) Modeling of Subsystem and Components
3) Power System Monitoring and Degraded System Management
4) Development of Engineering Data Base on New Technology Items
5) New Component Development Needs
6) Rotary Joints for Transmission of Power and Signals
7) Ni-Cd Battery Manufacturing and Application Technology
8) On-Array Power Management
9) High Voltage Technology Development
10) Solar Array/Solar Cell Testing
11) Engineering and Parts Standardization and Testing Standards
12) Interdiscipline Problems

The collection of problems in this format is reported in the next section.

Substorm and Plasma Design Data

The newly defined existence of plasma trapped in the Earth's magnetic field and its possibly catastrophic effect on high voltage, high power solar arrays points up an urgent need to adequately define the substorm environment so that solar arrays can be designed to survive this environment with minimum degradation.

Modeling of Subsystem and Components

Existing full-up analytical power system models are inadequate. Further, as the power system grows in complexity, the design and power management problems are amplified. Coupling this with extreme complications for complete end-to-end checkout of the power system implies that use of this tool is becoming a mandatory requirement for understanding and predicting performance margins.

In particular, accurate dc and ac models of each power subsystem component are required. Such models presently do not exist for solar arrays and batteries. Needed is a detailed analytical model of the ac (transient and small signal ac) performance for solar arrays. Immediate problems on Dynamic Explorer and Solar Maximum Mission that are related to the inability to test large arrays demonstrate the need for such models. Large arrays are too large to deploy and illuminate, and lightweight structures may even be too fragile to deploy in the presence of gravity. Once a model has been generated, it will be possible to design and build adequate simulators so that the overall power subsystem can be more fully tested. Also a detailed model of nickel cadmium batteries for both ac and dc conditions is required. Immediate problems of on-orbit failures suggest that the electrochemical system is poorly understood. As a result, power subsystem designs do not provide for all of the batteries' characteristics.

Power System Monitoring and Degraded System Management

The sensor complement used for power system monitoring is inadequate. All too often we have too few diagnostic techniques to accurately isolate the causes of problems. More sensitive and expanded sensors are needed for monitoring battery cell voltages, ampere-hour integration, charge/discharge current, relay and power transfer switch states, solar array power, and load current sensing. Automatic power system control should be supported, e.g., MSFC's Programmable Power Processor (PPP) and JPL's Auxiliary Power Subsystem Model (APSM).

Development of Engineering Data Base on New Technology Items

Because of project pressures to utilize increased solar cell efficiency (latest cell technology), the cell and cover characterization data concerning radiation and lifetime performance has not yet been generated or verified. This design data is necessary for today's array designs.

The Ni-Cd battery has a solid data base, but little if any of this type data baseline is available for the Ni-H_2 cell. Until it is available, Ni-H_2 battery programs will be difficult to sell to flight projects.

Power MOS devices are currently available from the manufacturers, but there has been no effort to qualify these units for flight in spite of their switching and low gate power advantages. The big question is their radiation susceptibility.

Microprocessors are going to be necessary for any housekeeping and management of power systems within the power system. It is necessary to select universal types which are flight qualified.

There are presently few if any high voltage, high power devices which can meet present and future needs. A large technology development is needed. The rejection criteria for these devices must be formulated with a verification test program to guarantee high reliability parts in a new and difficult environment which has not been successfully reduced by high voltage instrument technology transfer. This new environment is high voltage coupled with high temperature.

New Component Development Needs

The advent of high voltage, high power systems for Solar Electric Power Subsystem (SEPS), the Power Module, the Power Extension Package, and Erectable Space Platforms points up the need for components to operate at higher voltage and current levels. The SEPS solar array is configured with modules that operate at 196 volts at peak power, and these modules can be connected in series to provide higher voltages in integral multiples of 196 volts. The initial Beginning of Life (BOL) 31.6 kilowatt power level at the lowest operating voltage produces approximately 250 amperes. Transistors, relays, capacitors, connectors, and other distribution equipment must be developed to meet these voltage and current levels. In addition, power unique components are required to measure current on the solar array (because of the use of shunt regulators on the solar array to dissipate excess power), to measure nickel cadmium battery state of charge, and to detect and protect against faults.

Rotary Joints for Transmission of Power and Signals

High voltage, high power systems add a dimension to the past problem of transmission of 28 volt power and low level signals across a rotary joint. Possible techniques include rotary transformers, flexible harnesses, and slip rings for power and signals, and rf and optical coupling for signals. Additional work must be done in this area both because of past failures and present needs.

Ni-Cd Battery Manufacturing and Application Technology

Recent and frequent incidences of on-orbit degradation and failure of nickel cadmium batteries indicate a lack of uniformity in the original product and a lack of understanding of the correct application. The specific need has been identified for nickel cadmium long life design criteria, process standardization, electrochemical quality analysis methods, and reconditioning methodology to enhance operational performance for ten to twenty years on orbit.

On-Array Power Management

On-array power management has been a requirement with little actual development having been accomplished. On-array power management is required to reduce the signal rotating interface complexity, to place the heat at panel surfaces having lightweight construction and small thermal mass, and to provide power management flexibility over individual string current, voltage and power sensing, spot thermal control, panel or string problems due to degradation or environmental interactions, and current control of array overpower or overvoltage conditions. The concept also lends itself to advanced developments such as (1) three terminal solar cells, (2) photocontrollable cover slides, or (3) liquid crystal control covers.

High Voltage Technology Development

Numerous and varied high voltage designs are failing and/or are unreliable. In fact, failure of high powered traveling wave tube amplifiers was designated by a senior Air Force spokesman as the number one problem for communication satellites. All too often these failures could have been avoided by the application of the proper design, manufacturing, and test disciplines. Missing is a complete and detailed design guide (handbook) for high voltage equipment somewhat similar to the solar array design handbook. Also required is a detailed model high voltage procurement specification. The design guide should provide a set of recommended hardware design and analysis techniques and procedures. The model specification should contain detailed test techniques, methodology and acceptance criteria for piece parts, subassemblies, and top assemblies.

Solar Array/Solar Cell Testing

A nondestructive testing technique is required to verify the integrity of welds used to interconnect solar cells on high power solar arrays. Over one million welds are required in a large array. Various techniques have been utilized such as infrared scanning, laser holography, X-ray, and resistivity measurements, but these techniques are both expensive and inadequate.

Recent major problems have been encountered in applying "standard" humidity tests as process control tests. These tests are run at elevated temperatures in high humidity to accelerate corrosion of the contacts if impurities enter the contact processes. These tests are not compatible with new high efficiency solar cells with back surface reflectors. No viable alternate process control test is available. A new test (or tests) needs to be developed and standardized for the new solar cells being implemented into hardware programs.

Engineering and Parts Standardization and Testing Standards

There appears to be a general industry-wide lack of standard or baseline data base for many of the power system related parts and components. This is principally lacking in testing techniques which are used as standard by the industry principally in battery cells, solar cells, and their process and control development. Discussion centered on generating guidelines and technology leadership from NASA. Nondestructive testing techniques for welded contacts and contact corrosion accelerated testing were raised as problems associated with this lack of technical leadership.

Interdiscipline Problems

Two power subsystem problem areas have been identified which involve technology in areas not covered by this workshop panel.

The high power levels and the drive to reduce weight have resulted in very lightweight structures to support large area solar arrays. These structures have very low natural frequencies and will interact with the attitude control system.

Thermal control systems of existing spacecraft have failed to maintain the nickel cadmium batteries at the required temperature range, either because of a lack of understanding of battery dissipation or an inadequate thermal design.

SUMMARY OF RECOMMENDATIONS

The recommendations made of the members of the Power Subsystems Panel are summarized in the following paragraphs.

Substorm Plasma Effects

1) A simulation of the space plasma environment must be developed for ground testing of effects on electrical power systems. A determination is to be made of the energy profile, where it will flow, and how it will be dissipated in the spacecraft systems.

2) It is recommended that the spacecraft charging program at Lewis Research Center be supported by adding this study element to their program.

Analytical Modeling of Power System and Its Components

1) Perform alternating current modeling of the major power subsystem components by analysis. Verify by test, collecting sufficient data points to validate the analytical models assumed for the solar array, battery, and power conditioning and distribution. Define frequency range over which testing should be performed. Synthesize individual components into a single analytical model of a power system.

2) Define a set of parameters necessary to implement electronic simulation of an alternating current model of a solar array.

Improved Monitoring and Operation of Power System

1) Develop improved on-board techniques for monitoring and controlling operation of the power system and its major elements.

a) Develop software and/or hardware techniques that result in minimum impact to the spacecraft data handling/command system and to ground operations. For instance, reconfigure telemetry format for specific mission phases.

b) Identify required diagnostic measurements to allow determination of power system state of health.

c) Develop sensors and/or sensing techniques for detecting partial failure or degradation of key components such as battery, solar array, and power conditioning. Parameters to be directly measured or calculated shall include:

- Battery depth of discharge and state of charge
- Battery cell voltages
- Solar array parameters to include partial shunt currents and subarray currents and voltages

- Solar array output power and maximum available power
- Power distribution bus voltages, current, and power
- State (position) of all relays

2) Define techniques for reducing the complexity of managing degraded power system and components from ground and thereby minimize reliance on ground analysis and control.

Engineering Data Base Development

1) Develop an engineering data base on emerging technologies.

New Component Development Needs

1) High voltage, high power components are required for immediate use on flight power systems. These parts must be developed; new, reliable screening techniques determined; and flight qualification accomplished.

2) Specific items recommended include:

a) Families of switches and resettable circuit breakers over the following ranges:

500 V dc, 300 V dc, 150 V dc
10, 25, 50, 100, 150 amps

b) Capacitors, polarized, energy storage high capacitance voltage filter at greater than 150 V dc

c) Connectors, power wiring, slipjoint power, 300 V, 600 V, 1 kV dc

d) HV signal components

300 V, 600 V, 1 kV dc

Rotary Joint for Transmission of Power and Signals

1) Develop a combination rotary power and duplex transformer configured to provide 500 wattage (electrical) with data channels operating in the megabit range and in a parallel digital simplex mode for increased reliability and reduced noise.

Nickel-Cadmium Battery Manufacturing

1) Continue (with high priority) technology development for reconditioning and cell manufacturing process optimization and standardization.

2) Modify on-going process selection and standardization work to emphasize electrochemical and physical analysis methods development needed to provide better understanding of electrochemical fundamentals of plate processes, process variability and quality control, and charge/discharge processes.

High Voltage Technology Development

1) Develop a detailed HV design guide handbook and a model detailed HV procurement specification for spacecraft applications.

2) The design guide should provide a set of recommended hardware design and analysis techniques and procedures. It should also contain a detailed parametric materials properties data base and recommended test procedures and techniques for obtaining the necessary materials data.

3) The model specification should contain detailed test techniques, methodology and acceptance criteria for piece parts, subassemblies and top assemblies. It should also contain requirements for the types and detail of analytical techniques necessary to verify each design.

Array Interconnect Process Control, Product Verification, and Accelerated Life Testing

1) Continue (with high priority) the development of specific techniques for controlling the process involved in making reliable interconnections, for verification of flight hardware interconnect integrity, and for conducting accelerated corrosion testing on solar cell interconnects.

PRIORITIZED RECOMMENDATIONS FOR POWER SUBSYSTEMS

After the individual technology items were developed and the recommendations formulated, a prioritization was initiated. Factors which were to be considered were discussed. These factors included payoff (present need or future need), risk, and cost effectiveness. Since some items appeared to have essentially equal priority, it was concluded that grouping of degree of priority was needed, rather than absolute ordering of the 10 items in the list. Detailed discussion of the recommendations and rationale resulted in the following listing.

High Priority Items:

- Highest emphasis on new technology items -
  1) Modeling of Subsystem and Components
  2) Power System Monitoring and Degraded System Management
  3) New Component Development Needs
  4) High Voltage Technology Development
- Continue activity with existing program -

  Substorm and Plasma Design Data
- Modify existing program -

  Ni-Cd Battery Manufacturing and Application Technology
- Increase emphasis on ongoing activities -

  Solar Array/Solar Cell Testing

Medium Priority Items:

- Development of Engineering Data Base on New Technology Items
- Rotary Joints for Transmission of Power and Signals

Low Priority Items:

- On-Array Power Management

Not Technology Development:

- Engineering and Parts Standardization and Testing Standards
- Interdiscipline Problems

CHAPTER 5
REPORT OF THE ATTITUDE CONTROL AND ATTITUDE DETERMINATION PANEL

INTRODUCTION

This chapter presents the output of the Attitude Control and Attitude Determination Panel of the NASA Flight Technology Improvement Workshop.

The following approach was used by the panel in determining its recommendations:

1) Past failures and deficiencies in flight programs were reviewed with recommendations as to how they could be avoided.

2) The panel was divided into four subpanels covering the specific subareas of:

   a) Control system dynamics, analysis, and simulation
   b) Sensors and devices
   c) Software, estimations, and autonomy
   d) Designing, integration, and testing

3) Preliminary recommendations were prepared by the subpanels and presented to the whole panel for discussion. Final technology candidates were then chosen by the group as a whole. These technologies are not meant to be complete or all-inclusive, and reflect the background of the panel members.

TECHNOLOGY DEVELOPMENT PROBLEM AREAS

Control Configured Vehicle Design

A number of spacecraft have failed shortly after launch because they were unstable. These failures were manifested by the loss of the control system authority over the vehicle. When disturbances on the vehicle exceed the capability of the control system, the spacecraft and the mission are generally lost. With future spacecraft becoming larger, more flexible, and more complex, the problem of dynamic stability intensifies.

The possible dynamic interaction between the structure and the control system is a principal concern on every spacecraft. The difficulty in adequately modeling and predicting the control system performance before launch has been somewhat improved by development of sophisticated analysis tools for dynamic modeling and control synthesis. However, in most vehicle designs, the control system is not adequately considered as an integral part of the total spacecraft system, but rather it is generally thought of as being bolted on the structure. This ultimately leads to a more costly control system and structure, reduced performance, and greater risk. Therefore the thrust of this technology task is to develop the required technologies and design tools to make possible the design of future vehicles configured for a more effective integration of the control system. This effort will require integration of three principal technical areas during vehicle design: structures, dynamics, and control. A new modeling criterion for these future configured vehicles must be established so that a more effective analysis of vehicle performance can be carried out. Along with this criterion, new and improved control synthesis techniques can be developed which will lead to more robust systems, that is, systems which are less sensitive to system or component changes during the mission lifetime.

The output of this technology task will greatly assist in the reduction of costs for future complex systems and will reduce the risk in meeting performance goals. Lastly the technology has broad application to all future space vehicles (e.g., platforms or stations).

Gyros

High accuracy, long life devices for sensing spacecraft inertial attitudes and rates will be a continuing requirement for spacecraft in both the near and distant future. Existing gyro technology to satisfy this need is based on mechanical technologies and is sensitive to the well-known failure modes and finite life associated with bearing lubrication and gas flotation contamination systems.

There are several emerging technologies that offer the potential to either replace existing devices or augment the technology in specific applications. Some of these offer the inherent stability and reliability of solid-state equipment. Examples of possible technology are laser gyros, gyros utilizing the principle of nuclear resonance, electrostatic gyros, cryogenic gyros, and others.

These alternative devices have, in specific instances, moved out of the laboratory and into the working environments of aircraft and missiles. A concerted effort to rigorously examine and develop their potential for the unique requirements of spacecraft - extremely long life, high precision, and comparatively low rates - is an essential prerequisite for their future availability as a viable component.

Solid-State Star Sensor

Presently available attitude determination technology has neither the precision nor the flexibility to support many future missions, especially those at high altitudes. Current attitude determination methods are effective primarily at low altitudes and do not offer the high accuracy (approximately 1-2 arc sec) potentially required for many future spacecraft. Most systems are optimized for only one particular mission and are not readily adaptable to other missions. Also, precision attitude determination systems to date do not operate autonomously. Instead, they usually require extensive data processing support to be done on the ground. This can be costly and complex, and does not provide real time data.

Future satellites will require precise, real time attitude determination for some of the following purposes:

1) Precise pointing of narrow field-of-view and high resolution sensors (for better acquisition and tracking and reduced smear effects).

2) Precise target location through accurate determination of sensor line of sight.

3) Support of precise onboard navigation (position information is needed to augment attitude system, to support precise pointing of sensors, etc.).

4) Precise thrust vector alignment (insertion, stationkeeping, rendezvous navigation, on-orbit maneuvering, etc.).

5) Alignment determination and flexure monitoring of very large space structures (active shape control).

A principal element of many spacecraft attitude control and determination systems is a star sensor. Although a few star sensors already employ solid-state detectors (namely star scanners), the vast majority of star sensors in operation today rely on the limited capability of the Image Dissector Tube (IDT). IDT star sensors, however, suffer from certain fundamental limitations imposed by the construction of the tube itself. Limitations, such as the ability to track only a single star, electron multiplier gain instabilities, susceptibility to image deflections caused by external electric fields, high voltage requirements, and accuracy, make a replacement for the IDT highly desirable.

Recent advances in the development of charge transfer device technology, namely the Charge Coupled Device (CCD), now make a solid-state star sensor possible. A star sensor employing a CCD detector focal plane can achieve an order of magnitude better accuracy (attitude determination) than the current IDT sensors, and it is free of the problems inherent in IDT devices. A CCD star sensor has a fully active focal plane and thus has the capability to track multiple stars continuously as long as they are in the field-of-view of the sensor. The key advantage here is that several CCD star sensors can provide essentially continuous attitude information and therefore can operate in an all stellar mode without the need for gyros.

Some future satellite programs (i.e., large antennas, solar power systems, etc.) will involve the development of very large space structures which will require precise structural shape control. For many of these applications, it will not be feasible to use autocollimators because of visibility and distance constraints. However, a single CCD star sensor could provide three-axis attitude information by simultaneously tracking several stars. Independent, compact star sensors at remote locations could provide a means of relative alignment determination and flexure monitoring without range or relative visibility constraints. Both NASA and the Air Force share common interests in these types of applications.

There appear to be two classes of sensor requirements: a moderate accuracy star sensor to replace the present standard star tracker and a very accurate system for applications requiring 2 arc seconds and better performance.

Based on the rationale mentioned herein, it was the unanimous opinion of the group that NASA should actively pursue the development, acquisition, and operational employment of a CCD star sensor. The JPL has some experience with CCD star sensor design with their engineering model of the stellar sensor. The Air Force has an active CCD star sensor development program underway (MADAN program). In addition, other services and industrial firms are pursuing CCD star sensor technology. An interagency working group was recently formed between the Air Force Space and Missile Systems Organization and the JPL to address the feasibility of a joint CCD star sensor development program. Preliminary estimates have indicated a potential savings to the government of about 3 million dollars if a joint program could be agreed upon. In that case, the prototype CCD star sensor could be tailored to both agencies' requirements and could be available as early as 1982. NASA's vigorous support of the interagency star sensor working group would appear to be prudent.

Control Instrumentation

Presentations made by panel members which addressed on-orbit experience demonstrated a clear and significant lack of the means to understand readily and thoroughly on-orbit behavior and performance. In the context of significant increases in system complexity and limitations of both ground-based test and predictive analyses, strong motivation exists for the development of the necessary on-orbit instrumentation and related technology. This will insure demonstrable knowledge of on-orbit behavior and enhance the potential to achieve ultimate performance with both reduced risk and cost. In some cases, such instrumentation can be viewed as essential to achieving the required performance.

The panel anticipates the technology to require a fresh approach which allows both on-orbit and ground-based evaluation. The control instrumentation technology focuses on the development of instrumentation and sensing techniques required for determination of position and rate of articulated elements, relative alignment of spacecraft elements, shape control, etc. Other attitude and rate sensors are the subject of a separate task.

Development of the methodology and technology for on-board monitoring, and assessing of performance is also important. This includes not only the instrumentation techniques but also the technology related to on-board real-time decision making for data reconstruction (post-factum detail assessment) and the implementation of such a capability (data processing and storage, interfaces, etc.).

Technology development for self-test at the system (or component group) level and for built-in test at the component level is also an element of this task. This needs to be addressed from the standpoint of instrumentation technology as well as hardware complexity and feasibility for implementation. The application must include integration of this technology with ground test (bench, subsystem, and spacecraft level) as well as system level design for overall on-orbit performance monitoring.

Demonstration of the effectiveness of such technology is essential. Furthermore, key hardware and software technology elements must be developed to a level which would insure reliability for incorporation into flight programs.

Tolerant/Accommodating Control Systems

Both near-term and next generation spacecraft required to meet high performance objectives will have to be sufficiently cost effective and low in risk while satisfying the performance objectives. One way of accomplishing this is to extend the control configured design philosophy to include system configuration changes after flight initiation. Three specific areas are recommended for investigation.

1) On-orbit/ground calibration, reconfiguration, and adaptive control. Observation of overall system performance using either on-board instrumentation and diagnostic data processing or ground-based data processing may suggest or necessitate desirable changes in attitude control, payload control, or stability augmentation system characteristics. Both on-line and off-line methods to readjust or reconfigure these control systems are required when plan parameter and modeling uncertainty and/or unreasonable physical size make ground verification of performance inadequate to bound the risk of on-orbit failure. Methods incorporating identification before control (discussed below) or real-time adaptive or so-called learning systems might be considered.

2) Microprocessor-based or array-processor-based algorithms for structural dynamics identification. Identification of plant dynamics plays several roles in the design of advanced control configured type spacecraft. Analytical models used to synthesize controls must be verified and subsequent modeling errors quantified. This establishes requirements for parameter insensitive capability in control system synthesis and provides criteria for evaluating the meaning and validity of ground tests. In addition, fast, efficient identification algorithms allow both evaluation of closed-loop system performance vis-à-vis the original design goal and modification of the control law based on accurate knowledge of on-orbit system dynamics.

3) Demonstration of system level architecture design techniques. The principal intent of this task is a hardware demonstration of a reconfigurable system using both system identification and resynthesis of control laws to accommodate unanticipated changes in the vehicle/payload system.

Large Momentum Exchange Device

Momentum storage requirements increase rapidly as a function of spacecraft size. Future large spacecraft will require considerably larger momentum storage and transfer capability than presently exists in the Skylab control moment gyros. The purpose of this task is to identify the requirements for future momentum storage devices and the technology developments required and to initiate development of a prototype or brassboard model of such a device. The Annular Momentum Control Device (AMCD) developments are representative of the type of technology that may be required; however, whether or not the AMCD is the proper approach is uncertain.

The necessity for this work arises from the fact that neither the requirements nor the existing technology can realistically be scaled up through the required order-of-magnitude increase in size.

The benefits of this work are to provide realistic momentum storage equipment designs and confidence in the technology necessary to support near-term large spacecraft (such as the Power Module and Erectable Space Platforms) design and development activities.

Autonomous Rendezvous and Docking

There is a gap between the technology and the proven systems for accomplishing automatic rendezvous and docking. Many techniques have been proposed and analyzed. During the Gemini/Apollo time period some of these techniques were flown in six-degree-of-freedom laboratory simulations. Actual rendezvous and docking in the U.S. space program has always been done under astronaut control, whereas the U.S.S.R. has used automatic techniques, both in near-Earth missions and in a lunar sample return.

Future applications for a fully-automated system include:

1) Planetary sample returns where the two-way light time precludes real-time manual control.
2) On-orbit assembly of large structures in high orbits, including docking and latching of very long structural interfaces.
3) Recovery or close inspection of disabled or unknown orbiting bodies.
4) Capture of asteroids or meteorites.
5) Remote resupply of spacecraft or spacelabs.

Additional Concerns for Consideration

During the discussion of the Attitude Control and Attitude Determination Panel, there were several historical deficiencies identified which could be avoided in future systems without the performance of new work in the technology, device, or technique areas. The panel, however, feels that these areas deserve centralized attention by NASA in order to exchange experience among projects and to preclude repetition of deficiencies experienced in the attitude control and determination area to date. These areas are design and testing, fault tolerance, and information exchange.

Many instances of inadequate pre-launch testing have been reported. The problem is driven by several pressures: schedule time, complexity of the hardware and software, inadequate test facilities, and weak correlation of the system requirements, its design, and the test planning.

Techniques and computer tools are evolving (primarily for use in software design and test) which could probably be adapted to overall Attitude Control and Determination (AC&D) subsystem design and test. Some of these techniques are (1) top-down structured definition of requirements and design, (2) programs for cross-checking requirements compliance and compatibility, and (3) flow charters. Although much of the AC&D system is hardware, its functions are normally modeled in software for analysis and simulation and could be made compatible with this approach.

This approach

1) Better insures that no design or test oversights exist.

2) Provides an organized approach to design and test of increasingly complex systems.

3) Helps to design a complete test program which avoids duplication, but can still highlight important parameters for trend analysis throughout the design, test, and flight.

4) Provides a clear road map to aid management in making costs and schedule decisions.

Experience has indicated the practical advantage of a broadly based approach to fault tolerance. In the specific area of AC&D, the practical utility of generically dissimilar backup approaches has been proven to substantially enhance system fault and damage tolerance, although the advantages are difficult to demonstrate using classical reliability analysis, and the additional hardware and design required is typically difficult to justify on a project-by-project basis.

Coordinated planning and requirement definition would maximize the efficiency of implementation of backup approaches, enhance the coordination of the overall AC&D system, and insure that the benefits of previous experience are realized. Many of these goals are difficult to achieve within the environment of constrained program resources.

In the attitude control area as well as in other areas of this workshop, it has been emphasized that a technology data bank should be established and maintained. In addition to including historical and general data on the various AC&D devices, it would be most helpful to share on-orbit flight successes, failures, and anomalous behavior along with a knowledgeable contact. At one point in time, NASA maintained a document similar to this in the form of nomographs. This was discontinued several years ago. In addition, the Space Systems Technical Committee of the AIAA also maintained such a log until it became too large and expensive for the organization to handle. At the present time, the panel does not know of any centralized location or summary of this information.

The panel feels that a rich legacy of spacecraft experience exists, and if it were disseminated, it would be potentially useful for future design activities. Problems already experienced could be prevented in the future.

SUMMARY OF RECOMMENDATIONS

The following paragraphs summarize the recommendations of the Attitude Control and Attitude Determination Panel.

Control Configured Vehicle Design

1) Integrate control, structure and dynamics design/selection.

   a) Establish modeling criteria, modeling, and simulation techniques

   b) Develop and demonstrate control synthesis techniques for robust/insensitive design

Control Instrumentation and Sensing

1) Develop high performance, moderate cost, long life attitude/rate sensors, such as:

   a) Gyros

   b) Solid-state Star Sensor

2) NASA support an assessment and appropriate development of non-conventional gyros (lasers, etc.).

3) NASA support development of charge transfer device star sensor technology.

Control Instrumentation

1) Develop structural position/rate sensing and techniques.

2) Develop on-board diagnostics/performance/health monitoring and assessment.

3) Develop self-test, built-in test, and integration with ground test methods.

Tolerant/Accommodating Control Systems

1) Develop methods/techniques for on-orbit and ground calibration, reconfiguration and adaptive control.

2) Develop microprocessor/array processor based structural dynamics identification algorithms.

3) Demonstrate system level architecture design techniques.

Large Momentum Exchange Device

1) Identify requirements for large momentum storage devices, and initiate prototype development of a wheel or CMG suitable for large spacecraft control.

Automated Rendezvous and Docking

1) Develop methods, sensors, and system designs for automatic rendezvous and docking. Select at least one design and demonstrate in laboratory dynamic simulation.

Additional Development Areas

The following areas were identified as ones which deserve additional attention, possibly at the Chief Engineer level, while they do not require new technology, many historical deficiencies have indicated the importance of emphasis in these areas:

1) Development of well-structured design and test techniques.
2) Establishing and maintaining a data bank in the Attitude Determination and Control Technology components and systems.
3) Consideration of dissimilar backup approaches to provide fault tolerance.

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16. Abstract

The National Aeronautics and Space Administration sponsored a Flight Technology Improvement Workshop at the University of Maryland from July 31 to August 2, 1979. The purpose of the workshop was to bring together a group of space instrumentation experts from government and non-government agencies to discuss past spaceborne instrumentation technology deficiencies and current technology developments and to identify areas for potential improvement for future flight missions. Approximately 80 individuals participated in four panels covering the technology areas of: Optical Radiometric Instrumentation and Calibration, Electromechanical Subsystems, Attitude Control and Determination, and Power Subsystems.

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